

# Study the Forward-Backward Asymmetry of the Top Quark Production in the Randall-Sundrum Model with an Extension of Strong Interaction

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The large forward-backward asymmetry of the top quark pair production measured by the hadron colliders shed light on new physics signals beyond the Standard Model. In the Randall-Sundrum model with an additional  $SU(3)$  group in the strong sector, we compare the total cross section and forward-backward asymmetry of the top quark pair production with the newest data obtained by the CDF and the D0 collaborations. Our numerical analysis shows that the parameter  $c_q \gtrsim 0.5$ ,  $c_t \sim -0.6 \sim -0.8$ ,  $\tan \phi \gtrsim 20$  or  $\tan \phi \leq 1/20$  and the first excitation of axial gluon with a mass about  $5 \sim 6\text{TeV}$  can accommodate this large anomaly without violating other experimental constraints.

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## I. INTRODUCTION

Top quark physics is one of the most attractive topics of the current elementary particle physics, since the top quark is the heaviest fermion in the Standard Model (SM). It is considered to play an important role in probing the electroweak symmetry breaking mechanism and the new physics models beyond the Standard Model. Top quark has been extensively studied at hadron colliders. The total cross section of the top quark pair production at the Tevatron [1, 2] is in good agreement with the theoretical predictions of the SM [3–6]. Recently, the forward-backward asymmetry of top quark pair production has been measured

by the CDF and the D0 collaborations [7, 8]:

$$\begin{aligned} CDF : & 20.1 \pm 6.7\% \\ D0 : & 19.6 \pm 6.5\%. \end{aligned} \tag{1}$$

Theoretically, the forward-backward asymmetry of the top quark pair production from  $q\bar{q}$  annihilation at hadron colliders vanishes at leading-order. Due to the interference of gluon exchange tree diagram with the box diagram and interference between the initial and the final state gluon radiation, the next-to-leading-order QCD contributions to forward-backward asymmetry is about 6% [9–12], while the electroweak corrections can only contribute additional contribution roughly 0.2 % [13]. It indicates that the current experimental measurement of this asymmetry is about 2 standard deviation from the SM expectations [14], and even  $3.4\sigma$  effect has been claimed at large rapidity difference  $\Delta y$  and large invariant mass  $M_{t\bar{t}} > 450\text{GeV}$  from the CDF collaboration [7]:

$$A_{FB}^{t\bar{t}} = 0.475 \pm 0.114. \tag{2}$$

The ATLAS and CMS collaborations did not discover any deviations from the SM predictions within the experimental errors [15, 16], because initial states are almost charge symmetric due to gluon fusion at the LHC.

Right after this experimental indication, a series of NP models solutions have been proposed, such as an additional color-octet gauge boson [17–19], a new t-channel physics contribution [20, 21], a supersymmetric singlet [22], and so on [23]. In Ref. [24] a flavor-nonuniversal chiral color model has been discussed, where a parity violating light axial gluon  $M_A \sim 1.5\text{GeV}$  is preferred to give large forward-backward asymmetry.

The Randall-Sundrum (RS) model [25, 26] is one of the most compelling candidates of the NP models. Besides explaining the gauge hierarchy problem, the RS model also provides an elegant geometric solution to the fermion flavor puzzle. In the Randall-Sundrum model, the Kaluza-Klein (KK) gluons can generate forward-backward asymmetry at the tree level. Unfortunately, it is noted in Ref. [27] that the exchange of the KK gluons at the tree level is difficult to generate a remarkable forward-backward asymmetry without violating other phenomenological constraints.

In this paper, we will extend the Randall-Sundrum model with an extension of the strong interactions to include the KK axial-gluon. Similar to that in Ref. [24], we find that the

axial-gluon contribution in the RS model can also accommodate the experimental measured forward-backward asymmetry. However, our parameter range is quite different from that in Ref. [24], since we have to consider other phenomenological constraints for the entire RS model.

This paper is organized as follows: In section II, we present the model explicitly and point out the importance of axigluon that induces the forward-backward asymmetry at the Tevatron. We show the formulae of the cross section and the forward-backward asymmetry in section III. The numerical results are given in section IV. Finally, we give a brief summary in section V.

## II. THE MODEL

In the Randall-Sundrum model, two Minkowskian 3-branes located at 0 (Planck scale) and  $k\pi R$  (TeV scale) on the fifth dimension, where the bulk space is a slice of anti-de Sitter space with curvature  $k$  and radius  $R$ . If we assume all the Standard Model particles propagate in the bulk except the Higgs boson, which is assumed to localize around the TeV brane, we can avoid the dangerous higher dimensional operators, which can induce sizable flavor-changing-neutral-currents effects [28, 29]. The zero modes of the fermions can be localized either on the infrared brane or on the ultraviolet brane, which only depend on the mass parameters of different flavors [30]. Since the top quark is much heavier than the others, we naturally assume its zero mode is localized on the infrared brane with the mass parameter  $c_t < \frac{1}{2}$ , while the others are localized on the ultraviolet brane with the mass parameter  $c_q > \frac{1}{2}$ .

In the literature [31], an additional  $SU(3)$  group is added into the strong sector, which enlarges the strong interaction group to  $SU(3)_D \times SU(3)_S$ , where subscripts  $D$  and  $S$  indicate couplings to the  $SU(2)_L$  quark doublets and singlets, respectively. In this model, the so-called RS flavor problem [32], which refers to a fine-tuning of the KK mass to meet the CP-violating observable  $\epsilon_K$  in  $K - \bar{K}$  oscillation can be solved beautifully without violating the Randall-Sundrum-Glashow-Iliopoulos-Maiani mechanism [33]. The five-dimensional color-octet gluons  $G_M^D$  and  $G_M^S$  couple to the  $SU(2)_L$  quark doublets and singlets, respectively.

The interacting Lagrangian of the gluons and the quarks is as follows [31]:

$$\mathcal{L}_{int} = \sum_{r=1}^{family=3} g^D \bar{Q}_{rL} \Gamma^M G_M^D Q_{rL} + g^S \bar{U}_{rR} \Gamma^M G_M^S U_{rR} + g^S \bar{D}_{rR} \Gamma^M G_M^S D_{rR}, \quad (3)$$

where  $\Gamma^M = e_N^M \gamma^N$  is the five-dimension Dirac matrices and  $\gamma^N = (\gamma^\mu, i\gamma^5)$ .

A tiny modification of the minimal bulk gauge group  $SU(3)_C \times SU(2)_L \times U(1)_Y$  is needed, where a custodial symmetry is usually proposed in the electroweak sector [34] to meet the electroweak phenomenology (such as the oblique parameters  $S$ ,  $T$  and the  $Z^0 b\bar{b}$  coupling) [35–37] and flavor phenomenology (such as those in the  $K$ ,  $D$  and  $B$  physics) [38–40]. As a consequence, the KK scale  $M_{KK} > 2.4\text{TeV}$  is required [41, 42].

We should rotate the gauge group to recover five-dimensional Standard Model gluons  $G_M = \cos \phi G_M^D + \sin \phi G_M^S$ . As a byproduct, the axigluons  $A_M = -\sin \phi G_M^D + \cos \phi G_M^S$  emerge, where  $\tan \phi \equiv g^D/g^S$ . The five-dimensional strong coupling is  $g_s^{(5)} = g^D \cos \phi = g^S \sin \phi$  and the four-dimensional strong coupling is  $g_s = g_s^{(5)}/\sqrt{\pi R}$ .  $\pi R$  is the length of the orbifold, and  $k\pi R \sim 37$  is for stabilizing the gauge hierarchy from the Planck scale. So we can express the action of the axigluons and the fermions as:

$$S_{int}^A = \int d^4x dy \sqrt{-g} \sum_{i=1}^{flavor=6} (-\tan \phi \bar{\Psi}_{iL}(x, y) \Gamma^M \Psi_{iL}(x, y) + \cot \phi \bar{\Psi}_{iR}(x, y) \Gamma^M \Psi_{iR}(x, y)) A_M(x, y). \quad (4)$$

After KK decomposition and fixing the gauge  $A_M(x, y) = (A_\mu(x, y), 0)$ , we obtain

$$S_{int}^A = \sum_{i=1}^{flavor=6} \sum_{n=1}^{\infty} \int d^4x g_s (-\tan \phi \alpha_{nL}^i \bar{\Psi}_{iL}^{(0)}(x) \gamma^\mu \Psi_{iL}^{(0)}(x) + \cot \phi \alpha_{nR}^i \bar{\Psi}_{iR}^{(0)}(x) \gamma^\mu \Psi_{iR}^{(0)}(x)) A_\mu^{(n)}(x), \quad (5)$$

where  $\Psi_{iL,R}^{(0)}(x)$  are fermion zero modes, and  $A_\mu^{(n)}(x)$  are KK excitations of the axigluons, which have no zero modes naturally. The entanglement functions of the gauge boson and the fermion profiles are [29]

$$\alpha_{L,R}^{i,(n)} = \int_0^{\pi R} dy \frac{2(1 \mp c_{iL,R})}{e^{(1 \mp 2c_{iL,R})k\pi R} - 1} e^{2(1 \mp c_{iL,R})ky} \frac{k}{N^{(n)}} (J_1(\frac{M_A^{(n)}}{k} e^{ky}) + b_1(M_A^{(n)}) Y_1(\frac{M_A^{(n)}}{k} e^{ky})), \quad (6)$$

where  $b_1(M_A^{(n)}) \sim 0$  and  $N^{(n)} \sim 1/\sqrt{\pi^2 R M_A^{(n)} e^{\pi k R}}$ .

We take account only the first excitation of the axigluon for simplicity whose mass is  $M_A \sim 2.4 M_{KK}$  [31]. If we assume  $c_{iL} = -c_{iR} = c_i$ ,  $\alpha_L^{i,(n)} = \alpha_R^{i,(n)}$ , and denote  $c_q$  and  $\alpha_q$  for

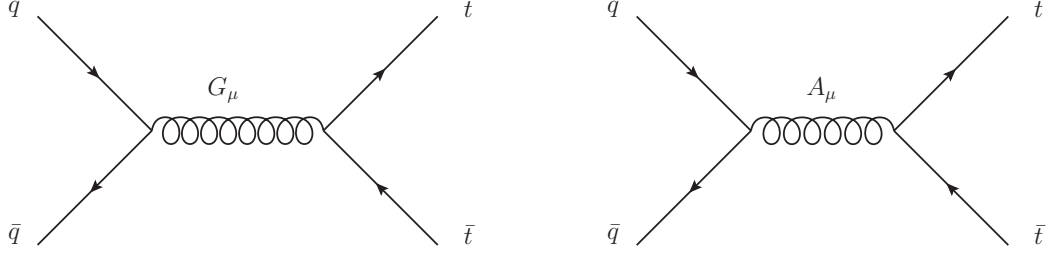


FIG. 1: The left Feynman diagram is the leading order contribution in SM to the  $t\bar{t}$  production, and the right one is the axigluon exchanging process at the tree level.

the light quarks while  $c_t$  and  $\alpha_t$  for the top quark, we can obtain

$$\mathcal{L}_{int}^A = \sum_{i=1}^{light\ quarks} g_s \bar{f}_i \gamma^\mu (f_L P_L + f_R P_R) f_i A_\mu + g_s \bar{t} \gamma^\mu (g_L P_L + g_R P_R) t A_\mu, \quad (7)$$

where  $f_L = -\tan \phi \alpha_q$  and  $f_R = \cot \phi \alpha_q$  and  $g_L = -\tan \phi \alpha_t$  and  $g_R = \cot \phi \alpha_t$ . The projection operators  $P_{L,R} = \frac{1 \mp \gamma^5}{2}$ . The emergence of the massive axigluon is curial to the asymmetry, since it violates parity symmetry in strong sector. In another word, it induces forward-backward asymmetry within CP conservation. We will show that in the next section.

### III. THE TOTAL CROSS SECTION AND THE FORWARD-BACKWARD ASYMMETRY OF $t\bar{t}$ PRODUCTION

At the Tevatron, the top quark pair can be produced at the leading order as in the first diagram in Fig. 1. In the Randall-Sundrum model, there is one additional diagram with exchanging axigluon as shown in the second diagram in Fig. 1. Since the total cross sections measured by the experiments agree well with the Standard Model calculations, the New Physics contribution should be much smaller than the SM results. The interference between the QCD Born diagram and s-channel axigluon exchanging diagram will induce the forward-backward asymmetry, since the axigluon breaks parity conservation.

The partonic differential cross section can be expressed as [23]

$$\frac{d\hat{\sigma}}{d\cos\hat{\theta}} = \frac{d\hat{\sigma}_{SM}}{d\cos\hat{\theta}} + \frac{d\hat{\sigma}_{INT}}{d\cos\hat{\theta}} + \frac{d\hat{\sigma}_{NP}}{d\cos\hat{\theta}}, \quad (8)$$

where  $\hat{\theta}$  is top quark polar angle in the partonic center-of-mass frame. The leading order

contribution is

$$\frac{d\hat{\sigma}_{SM}}{d\cos\hat{\theta}} = \frac{\pi\beta\alpha_s^2}{9\hat{s}}(2 - \beta^2 + \beta^2\cos^2\hat{\theta}). \quad (9)$$

The interference between the gluon exchange and the axigluon exchange contribution is

$$\begin{aligned} \frac{d\hat{\sigma}_{INT}}{d\cos\hat{\theta}} = & \frac{\pi\beta\alpha_s^2}{18\hat{s}} \frac{\hat{s}}{\hat{s} - M_A^2} [(g_L + g_R)(f_L + f_R)(2 - \beta^2) + \\ & 2(g_L - g_R)(f_L - f_R)\beta\cos\hat{\theta} + (g_L + g_R)(f_L + f_R)\beta^2\cos^2\hat{\theta}]. \end{aligned} \quad (10)$$

Apparently, the linear term of  $\cos\hat{\theta}$  here will give the forward-backward asymmetry. Finally the third term induced by the axigluons is

$$\begin{aligned} \frac{d\hat{\sigma}_{NP}}{d\cos\hat{\theta}} = & \frac{\pi\beta\alpha_s^2}{36\hat{s}} \frac{\hat{s}^2}{(\hat{s} - M_A^2)^2} [(g_L^2 + g_R^2)(f_L^2 + f_R^2)(1 + \frac{2g_L g_R}{g_L^2 + g_R^2}(1 - \beta^2)) + \\ & 2(g_L^2 - g_R^2)(f_L^2 - f_R^2)\beta\cos\hat{\theta} + (g_L^2 + g_R^2)(f_L^2 + f_R^2)\beta^2\cos^2\hat{\theta}]. \end{aligned} \quad (11)$$

The partonic center-of-mass energy  $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$ , where  $x_1, x_2$  are the fractions of proton and anti-proton momentum carried by parton 1 and 2, respectively.  $\sqrt{s}$  is the total center-of-mass energy of the hadron collider.  $\beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}$  is top quark velocity in the  $t\bar{t}$  center-of-mass frame. Here we assume that the mass of axigluon is larger than the colliding energy  $\sqrt{s}$  of the Tevatron by considering other constraints [41, 42].

The total cross section can be obtained by convoluting the partonic cross section with the parton distribution functions. The forward-backward asymmetry of the top quark pair productions is defined as

$$A_{FB}^{p\bar{p}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{\sigma_a}{\sigma_s}, \quad (12)$$

where the symmetric and anti-symmetric cross sections at the partonic level are defined as:

$$\hat{\sigma}_{s,a}(\hat{s}) = \int_0^1 d\cos\hat{\theta} \frac{d\hat{\sigma}}{d\cos\hat{\theta}} \pm \int_{-1}^0 d\cos\hat{\theta} \frac{d\hat{\sigma}}{d\cos\hat{\theta}}. \quad (13)$$

From Eq. (2), we notice that a proper cut on the invariant mass of  $t\bar{t}$  can enhance the signal/background efficiency in experimental measurements. Theoretically, we need to consider the  $t\bar{t}$  plus jet production. The typical Feynman diagrams are shown in Fig. 2. Practically, the invariant mass of top-antitop pair  $M_{t\bar{t}}$  can be expressed by jet energy  $E_j$  at LO:

$$M_{t\bar{t}}^2 = \hat{s}(1 - \frac{2E_j}{\sqrt{\hat{s}}}). \quad (14)$$

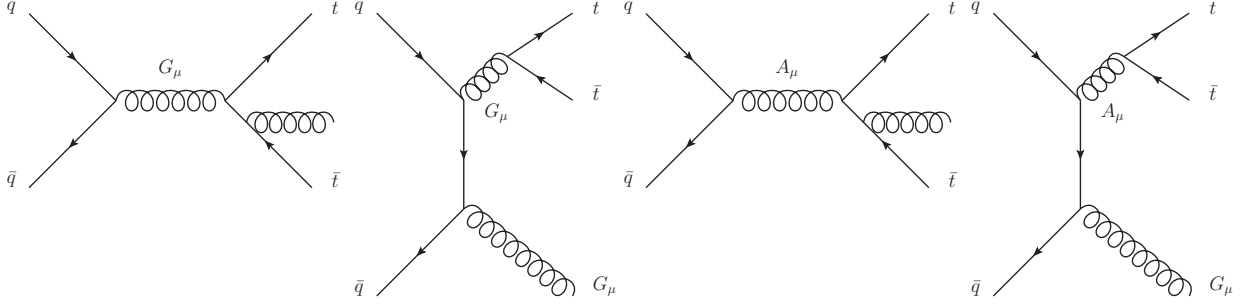


FIG. 2: The leading order s-channel and t-channel Feynman diagrams in SM for  $t\bar{t} + j$  production and the s-channel and t-channel axigluon exchange diagrams at the leading order.

#### IV. NUMERICAL RESULTS

The current particle physics experiments agree with the Standard Model predictions at a very high precision, therefore, every New Physics model has been severely constrained by the precision experiments. For the extra dimension model with custodial symmetry  $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ , the fit of the oblique parameters  $S$ ,  $T$  indicates  $M_{KK} \sim \mathcal{O}(1)\text{TeV}$  [34]. The flavor physics constraints studied in ref. [40–42] show that  $k\pi R \simeq 36.8$ ,  $c_t \in [-0.3, -1]$ ,  $c_q \in [0.5, 0.8]$  and  $M_{KK} > 1.2\text{TeV}$  are allowed.

In our numerical analysis, we use the the parton distribution functions CTEQ5 [43] to obtain the hadronic level results. Firstly, the experimentally measured  $t\bar{t}$  total cross sections will give a further constraint on the RS model parameters. We show the  $t\bar{t}$  cross section as a function of the axial gluon mass  $M_A$  in the left panel of Fig. 3, with the mass parameters of light quarks  $c_q = 0.51$  and top quark  $c_t = -0.6$ ,  $c_t = -0.7$ ,  $c_t = -0.8$  (three lines from bottom to top). The two dashed lines in the figure are the CDF experimental  $1\sigma$  band and dotted ones are the D0  $1\sigma$  band. At the right panel of Fig. 3, we also show the forward-backward asymmetry of  $t\bar{t}$  production as a function of  $M_A$  using the same model parameters. We take  $\tan\phi = 25$  to obtain a sizable asymmetries, which will be explained below. From Fig. 3, one can see that there is a maximum in the region of  $5 \sim 6\text{TeV}$  for the mass of axigluon preferred by the  $t\bar{t}$  experiments which indicate  $M_{KK} > 2\text{TeV}$ . The axial gluon mass dependence behavior of Fig. 3 reflects the entanglement Bessel functions in Eq. (6). Since the coupling of the axigluon to the top quark is much larger than that to the light quarks, the forward-backward asymmetry is enhanced only in the  $t\bar{t}$  final states.

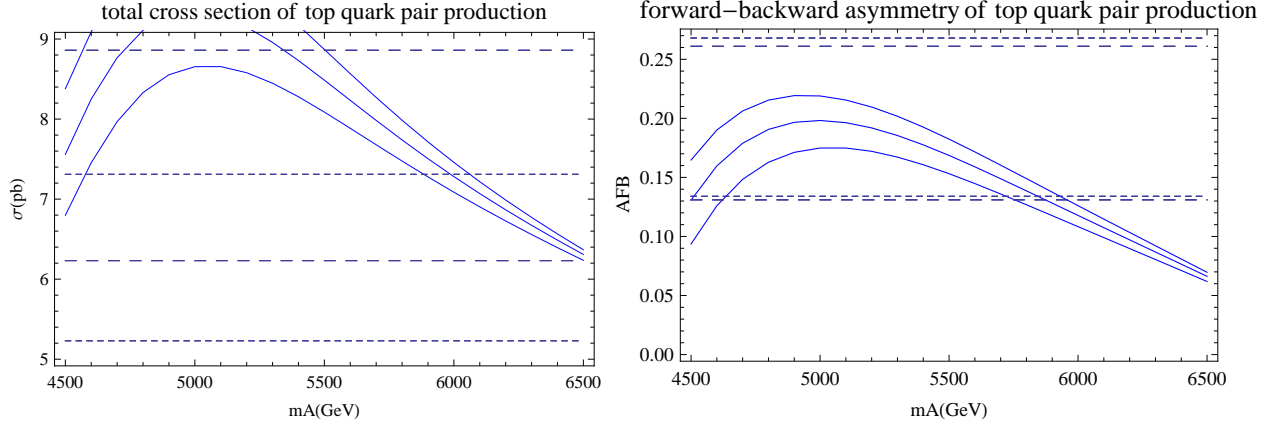


FIG. 3: The total cross section (left) and the forward-backward asymmetry (right) of top quark pair production as a function of axial gluon mass. The three curves from bottom to top in the pictures are for  $c_t = -0.6, -0.7$  and  $-0.8$ , respectively. Other parameters are chosen as  $c_q = 0.51$ , and  $\tan \phi = 25$ . The dashed lines are CDF  $1\sigma$  allowed bands and dotted ones are D0 data.

The smallness of the light quark profiles around the infrared brane is less important for the issue, so we only consider the top quark mass parameter. The difference between the light quarks and the top quark couplings to the axigluon is the origin of the forward-backward asymmetry in top quark pair production. The hierarchy of the fermion masses will increase the forward-backward asymmetry. When  $c_t$  increases, in other words, the mass of top quark decreases, the entanglement function is getting smaller and smaller. Therefore we obtain decent curves of both the total cross section and the forward-backward asymmetry within running  $c_t$ . This is explicitly shown in Fig. 4 as a function of  $c_t$  with  $c_q = 0.51$  and  $\tan \phi = 25$ . The total cross section of the top quark pair production is shown in the left diagram of Fig. 4, while the forward-backward asymmetry is shown in the right diagram of Fig. 4. The three curves from top to bottom shown in each diagram in Fig. 4 is for  $M_A = 5\text{TeV}$ ,  $5.5\text{TeV}$  and  $6\text{ TeV}$ , respectively. We use the dashed lines to represent the CDF experimental bands and dotted ones for D0 data.

Then we show the total cross section and the forward-backward asymmetry as a function of  $\tan \phi$  in Fig. 5, which is very important for model building. Here we set  $M_A = 5\text{TeV}$  and  $c_q = 0.51$ . The three lines at each diagram in Fig.5 are for  $c_t = -0.6, -0.7$  and  $-0.8$  from bottom to top. The left diagram in Fig. 5 is the total cross section of the top quark pair production, and the right one is the forward-backward asymmetry. The dashed lines express



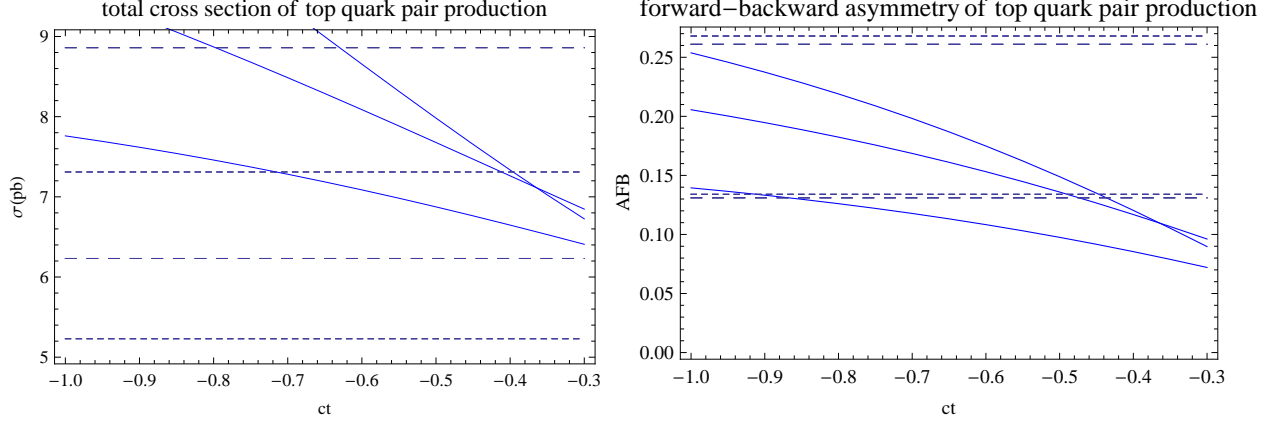


FIG. 4: The total cross section (left) and the forward-backward asymmetry (right) of top quark pair production as a function of top quark parameter  $c_t$ , with  $c_q = 0.51$  and  $\tan \phi = 25$ . The three lines in each diagram from top to bottom are chosen for  $M_A = 5\text{TeV}$ ,  $5.5\text{TeV}$  and  $6\text{TeV}$ , respectively. The dashed lines are CDF  $1\sigma$  bands and dotted ones are D0  $1\sigma$  data.

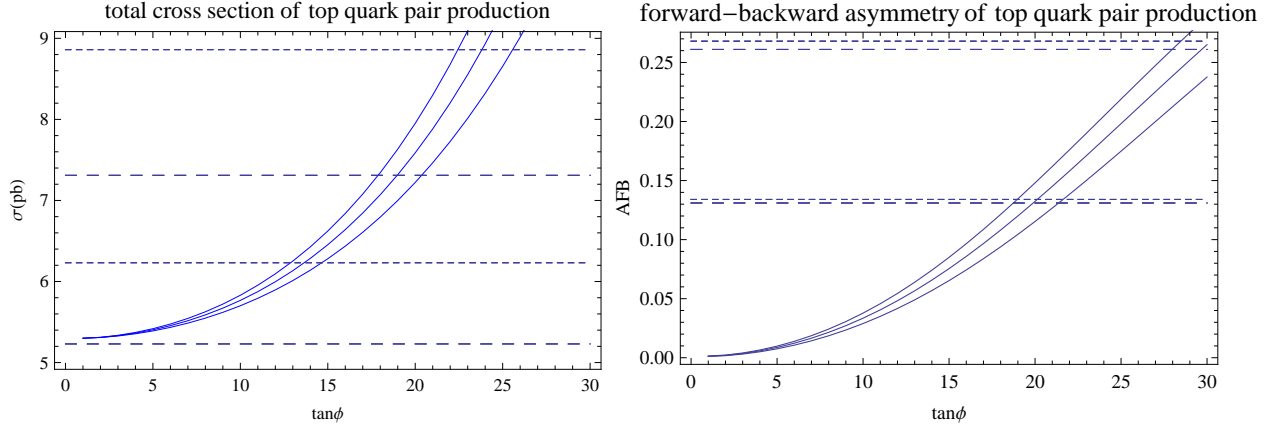


FIG. 5: The total cross section (left) and the forward-backward asymmetry (right) of top quark pair production as a function of  $\tan \phi$  with  $c_q = 0.51$  and  $M_A = 5\text{TeV}$ . The three lines at each diagram from bottom to top are for  $c_t = -0.6, -0.7$  and  $-0.8$ , respectively. The dashed lines are CDF bands and dotted ones are D0 data.

the CDF experimental  $1\sigma$  band and dotted ones is for D0 data. From Fig. 5, one can see that  $\tan \phi$  around  $\mathcal{O}(1)$  is not preferred. While  $\tan \phi > 20$  is allowed for a sizable forward-backward asymmetry in the  $t\bar{t}$  production, which is not accordance with the assumption in [31]. This means that  $g^D \gg g^S$ , so the gauge groups are hierarchy in the bulk. On the

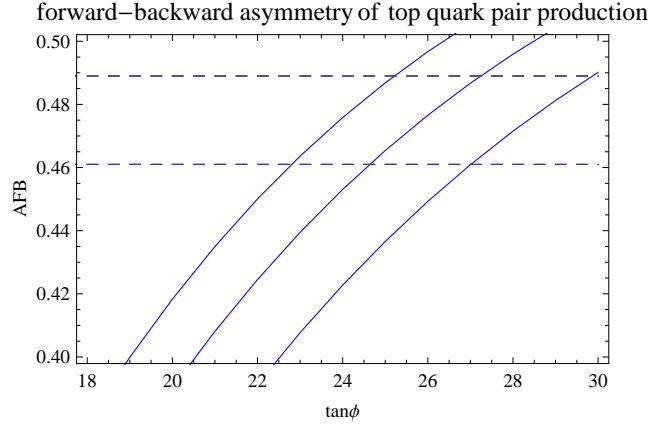


FIG. 6: The forward-backward asymmetry of  $t\bar{t}+j$  final states as a function of  $\tan\phi$  with  $c_q = 0.51$  and  $M_A = 5\text{TeV}$ . The three lines from bottom to top are for  $c_t = -0.6, -0.7$  and  $-0.8$ , respectively. The horizontal dashed line band is obtained by using CDF  $1\sigma$  data.

other hand, the computation is perturbative. If we set  $g^D \sim 1$  and  $g^S \ll 1$ , then the parity violation is very tiny even in the higher dimensions. We will have only one  $SU(3)$  group in the strong sector at low energy. Additionally, since the forward-backward asymmetry is proportional to  $\tan\phi + \frac{1}{\tan\phi}$  which is symmetric under transformation  $\tan\phi \rightarrow 1/\tan\phi$ ,  $\tan\phi \leq \frac{1}{25}$  is also acceptable. However, the hierarchy of the gauge group is unchanged.

Finally, as stated in the introduction, more effective experimental data for the forward-backward asymmetry is presented from CDF collaboration for the  $t\bar{t}+j$  final states. Our results are shown in Fig. 6, using a  $M_{t\bar{t}} > 450\text{GeV}$  cut to compare with the experimental data. Here we set  $c_q = 0.51$ ,  $c_t = -0.60$  and  $M_A = 5\text{TeV}$ . The horizontal band in the figure is obtained from the CDF  $1\sigma$  data. We are particular interested in the forward-backward asymmetry running with  $\tan\phi$ , which is consistent with the results shown in Fig. 5. From Fig. 6 we can see that with one additional hard jet, the constraint on the NP parameters are more stringent, since the asymmetry has been enhanced. A careful study will provide more information from exclusive production than the inclusive one.

In Ref. [24] a general flavor-nonuniversal chiral color model has been discussed, where a light axigluon  $M_A \sim 1.5\text{TeV}$  and a moderate mixing angle  $\phi \sim 30^\circ$  are preferred. However, since the other experiment constraints on the Randall-Sundrum model existed [40–42], our axigluon mass is much larger. In other words, a special parameter space is obtained for  $c_q \gtrsim 0.5$ ,  $c_t \sim -0.6 \sim -0.8$ ,  $M_A = 5 \sim 6\text{TeV}$  and  $\tan\phi \gtrsim 20$  or  $\tan\phi \leq 1/20$ , which is

consistent with other constraints. Therefore the parameter space of this model is severely constrained, which can be tested easily by experiments in the future. The axigluon is crucial to induce the forward-backward asymmetry in  $p\bar{p}$  collision, since it violates parity, and the difference between couplings to the top quark from the light quarks boost it significantly. The contributions of the higher KK excitations are suppressed by  $M_{KK}$ , so we can ignore them at present.

## V. SUMMARY

We computed the total cross sections and the forward-backward asymmetries of top quark pair production in the Randall-Sundrum model with enlarging strong sector to  $SU(3)_D \times SU(3)_S$ . Utilizing the recent CDF and D0 data of the forward-backward asymmetry, a special parameter space is obtained for  $c_q \gtrsim 0.5$ ,  $c_t \sim -0.6 \sim -0.8$ ,  $M_A = 5 \sim 6\text{TeV}$  and  $\tan\phi \gtrsim 20$  or  $\tan\phi \leq 1/20$ , which is also consistent with data in flavor physics and electroweak precision tests.

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